Exotic spectroscopy

Compact Pentaquark structures

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arXive:1604.03769

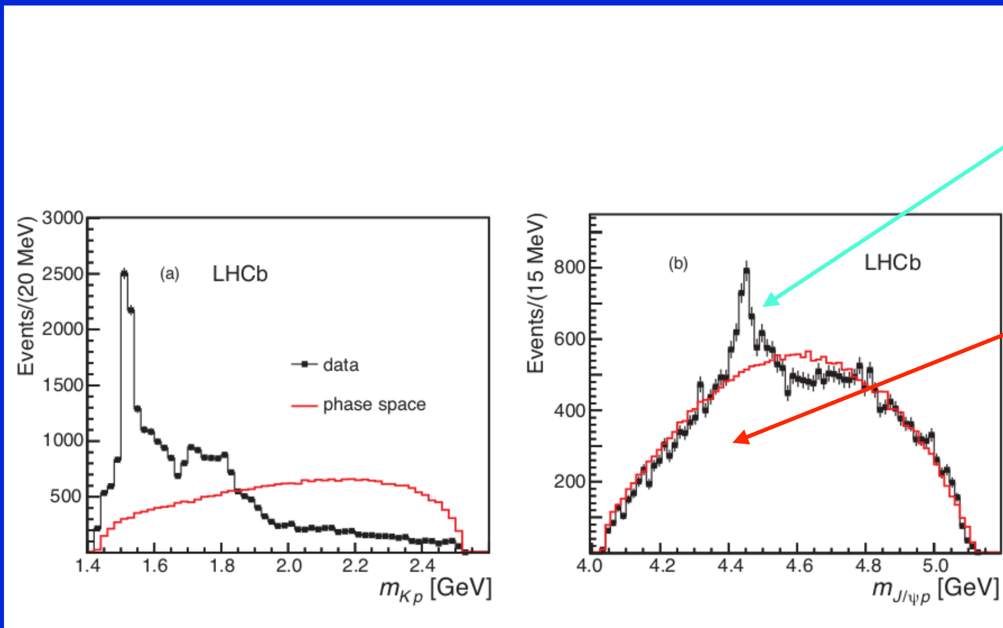
Gell-Mann and Zweig 60ties
suggested also the existence of penta and tetra quarks

M. Gell-Mann, Phys. Lett. **8** (1964) 214. doi:10.1016/S0031-9163(64)92001-3

G. Zweig, CERN-TH-401.

LHCb, one of the great experimensts at the
Large Hadron Collider LHC,
has observed in the study of the decays of
the heavy baryon Λ_b,
a new class of exotic particles

LHCb



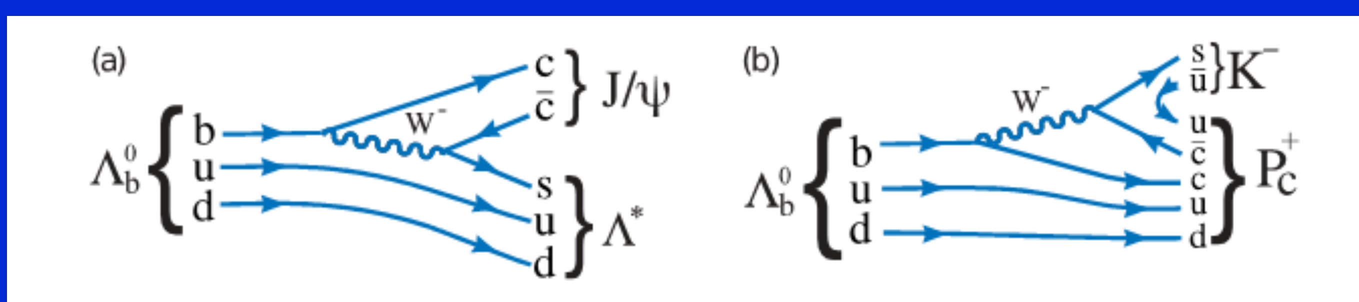
$P_C^+(4450) = (4449.8 \pm 39)$ MeV

$P_C^+(4380) = (4380 \pm 205)$ MeV

statistic signifiance greater then 9 sigma !

$$\Lambda_b^0 \longrightarrow J/\psi + \Lambda^*, \Lambda^* \longrightarrow K^- + p$$

$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



What has LHCb observed?

simulation of decays as from LHCb

santopinto, giachino, hep-ph 1604.03769

- We use very general arguments dictated by symmetry considerations, in order to describe pentaquark states within a group theory approach. A complete classification of all possible states and quantum numbers, that can be useful both to the experimentalists, for new finding, or to theoretical model builders are given, without the introduction if any particular dynamical model.

- Some prediction are finally given using a Guersey-Radicati inspired mass formula. We reproduce the mass and the quantum numbers of the lightest pentaquark state reported by LHCb (JP = 3 /2−), with a parameters free mass formula fixed on known well established baryons.

- We predicted the other pentaquark resonances (giving their masses, and suggesting possible decay channels) which belong to the same multiplet of the discovered one.

Construction of the states

1) a pentaquark state should be a color singlet $SU_c(3)$

↓

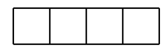
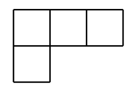
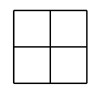
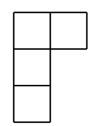
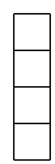
the antiquark $\bar{c}$ transforms as $\bar{3}$ so the color representation of the 4 quarks subsystem has to be the [211] state (with permutation symmetry F1)

2) be antisymmetric under any permutation of the four quarks (Pauli principle)

1) + 2) the two conditions determine the kind of symmetry for the orbital-spin-flavour 4 quarks subsystem

By the second condition, the orbital-spin-flavour part of the w.f., ψ, is necessarily a [31] state with F_2 symmetry, which is obtained from the colour state [211], by inter-changing rows and columns. In fact, the [211] and the [31] state are one the conjugate to the other, and so their product give the completely antisymmetric state [1111], with symmetry A_2

Table 1: permutation symmetries of the four quark subsystem of the pentaquark states (see [14]). Each Young tableau ($[f_i, ...f_n]$), with the corresponding multiplicity, is reported. The different labels (A_1, F_2, E, F_1,A_2) simply encodes the kind of symmetry of a given Young tableau, which is symmetry for the rows and antisymmetry for the columns.

Symmetry		$[f_i, ...f_n]$	Young tableau	Multiplicity
A_1	$\sim$	[4]		1
F_2	$\sim$	[31]		3
E	$\sim$	[22]		2
F_1	$\sim$	[211]		3
A_2	$\sim$	[1111]		1

Construction of the states

We know the 4 quark symmetry

↓

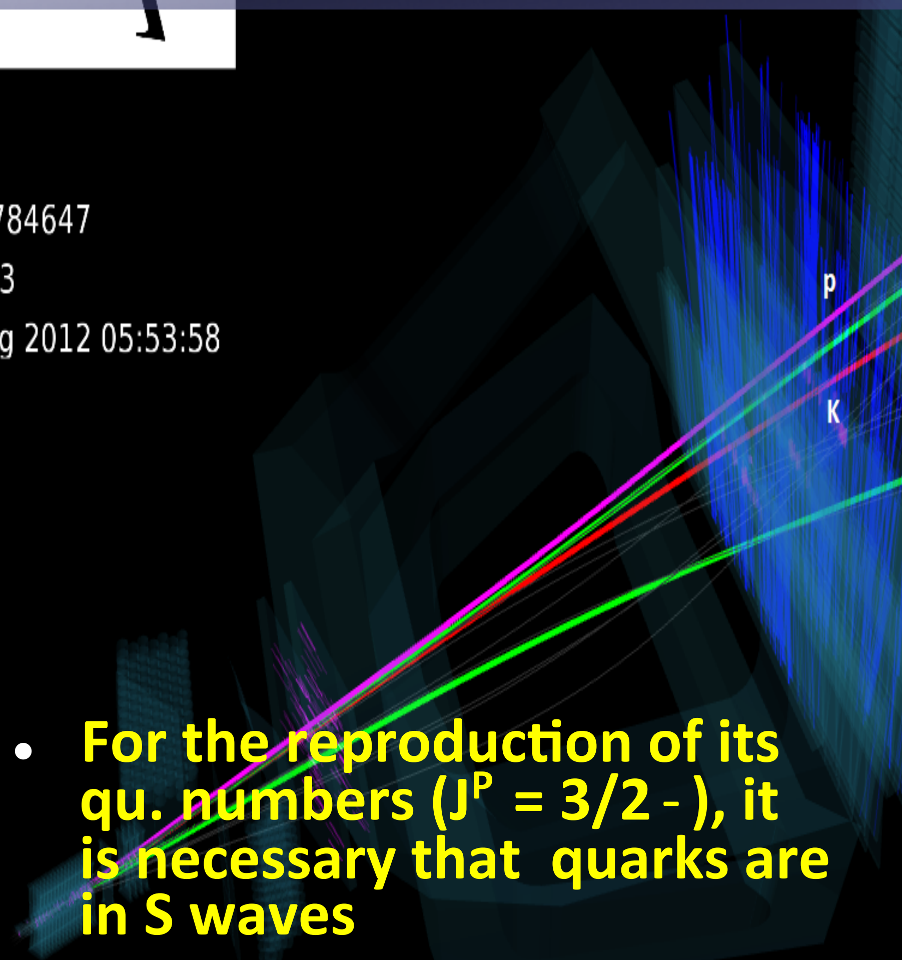
We obtain the SU(8) spin-flavour representations compatible with symmetry principles

Pentaquark resonance P_c+(4380)

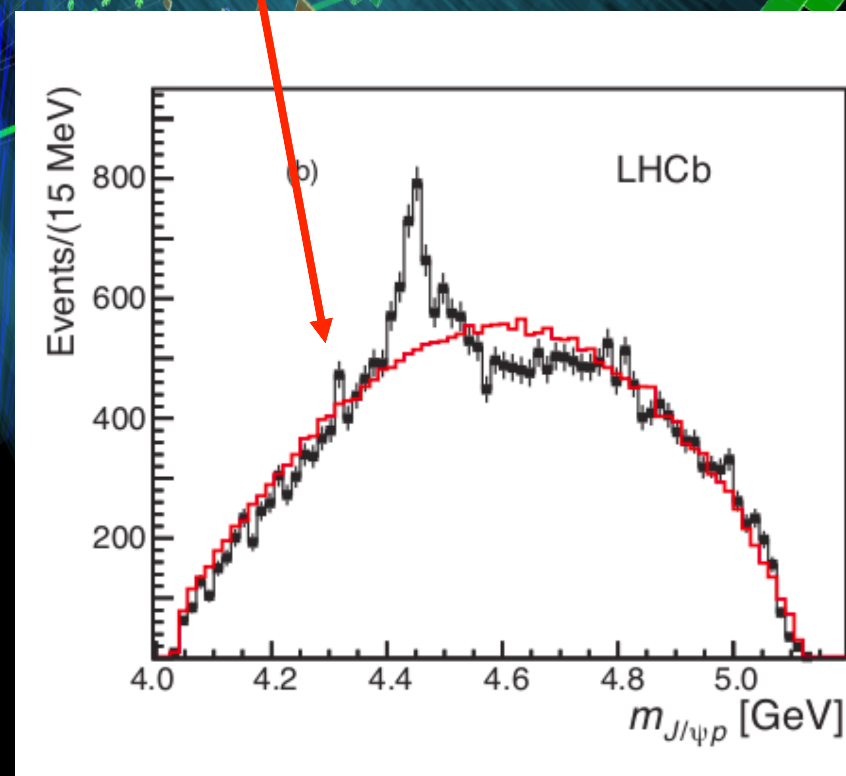
Event 251784647

Run 125013

Thu, 09 Aug 2012 05:53:58

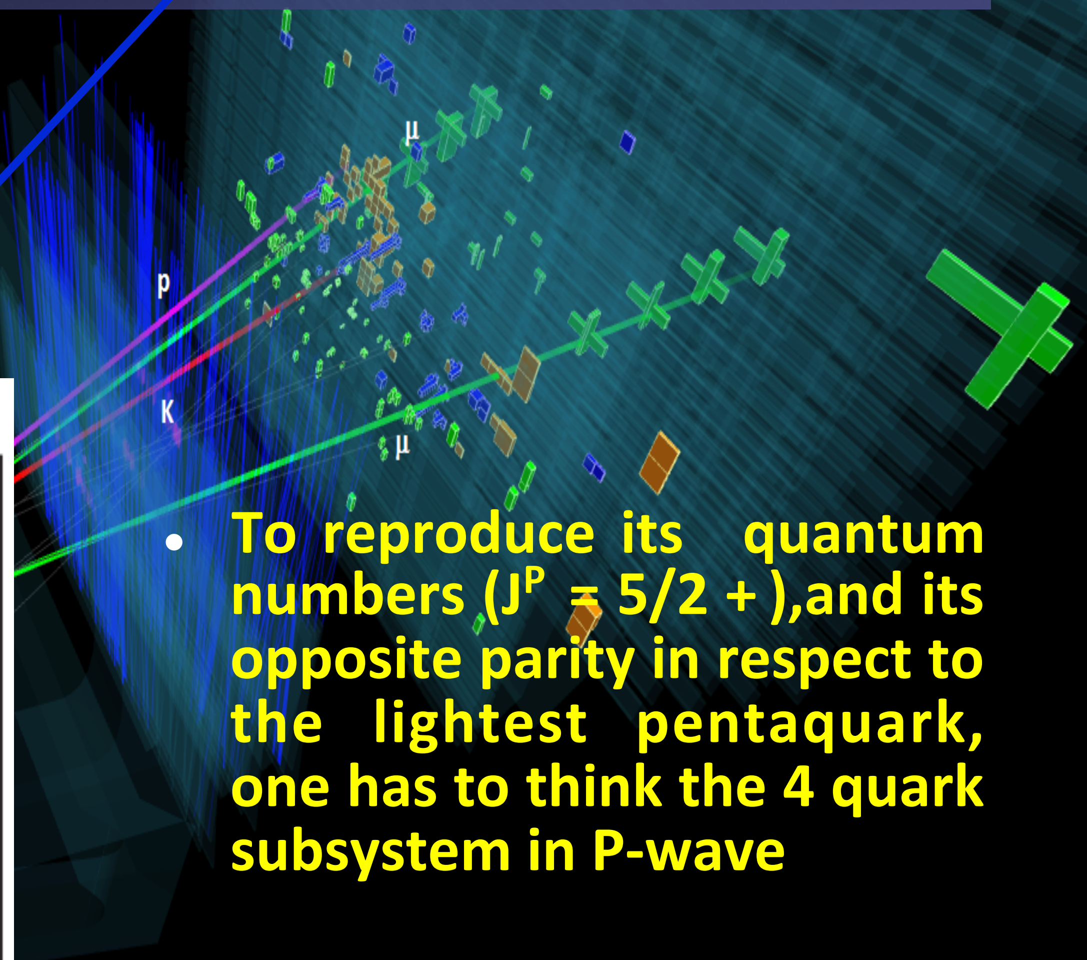


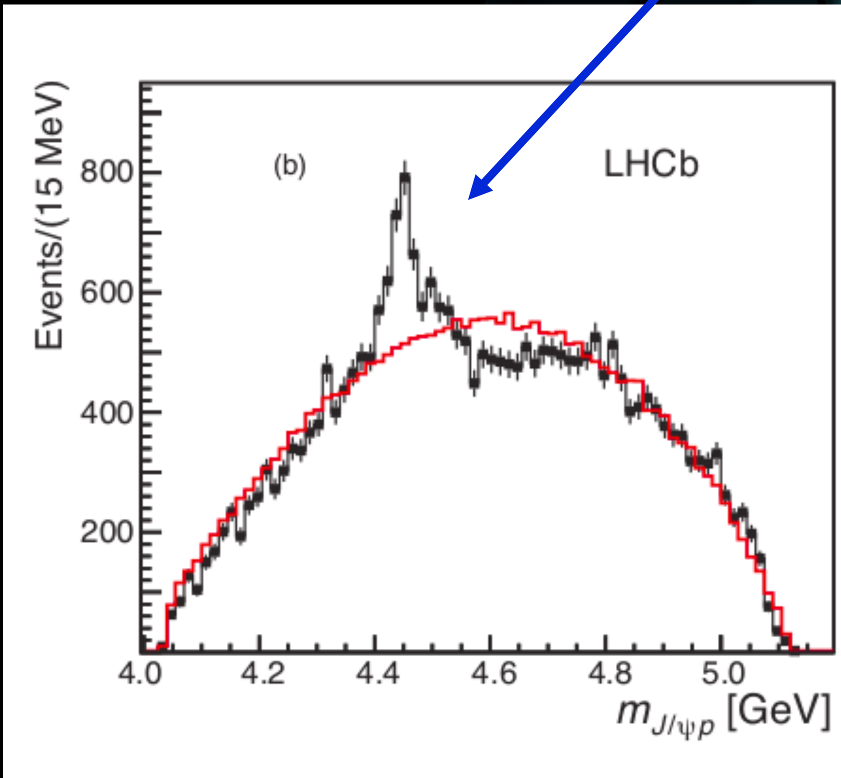
- **For the reproduction of its qu. numbers (J^P = 3/2 -), it is necessary that quarks are in S waves**



The pentaquark P_c+(4450) resonance

Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58





- To reproduce its quantum numbers (J^P = 5/2 +),and its opposite parity in respect to the lightest pentaquark, one has to think the 4 quark subsystem in P-wave

Compact pentaquark or molecular states?

The heaviest resonance , P_c+(4450),
has a mass close to the threshold of $\Sigma c \; D^{*}$ (4462.4 MeV)

↓

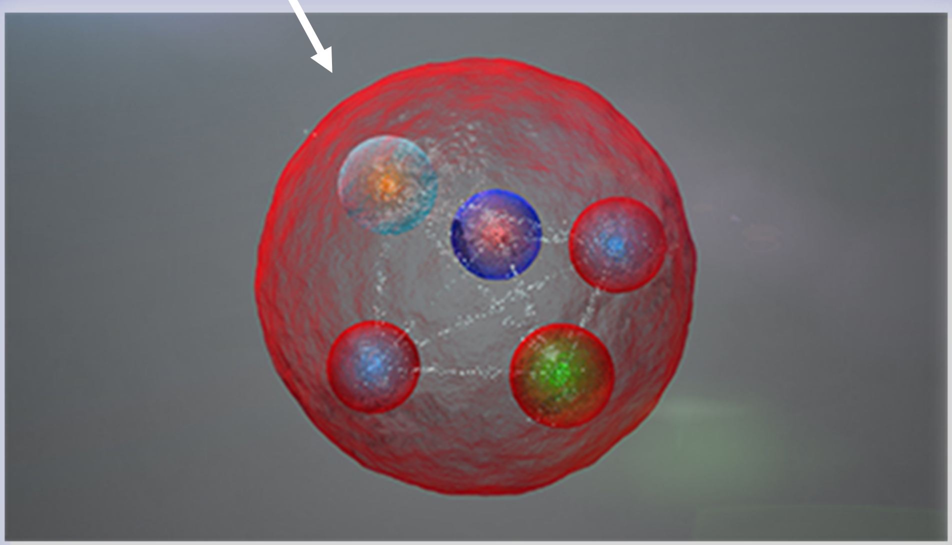
This suggest that this state can not be explained as compact pentaquark, but in first approximation as a molecular state

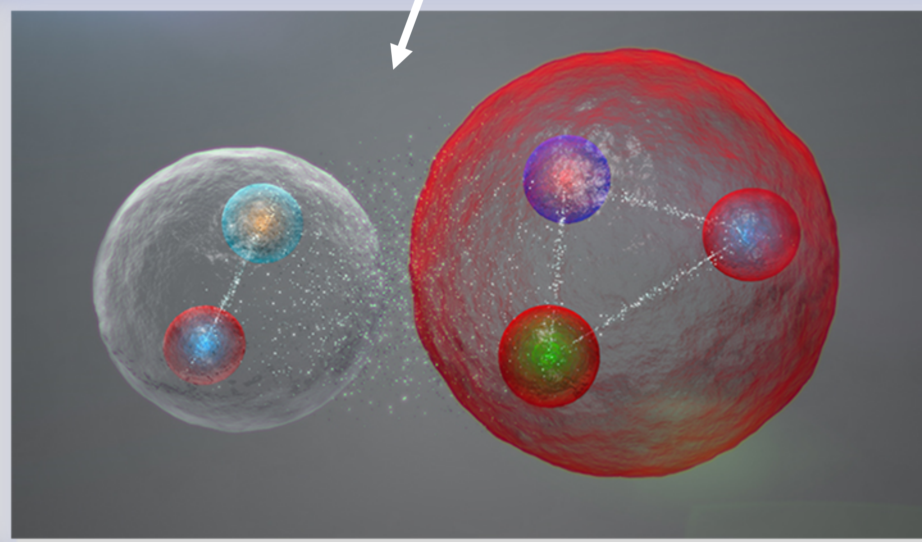
Karliner & Rosner interpretation

The hypothesis that the higher state, P_c+(4450), is a molecular state is in accordance with Karliner e Rosner's work

IN CONCLUSION:

P_c+(4380)	P_c+(4450)
Compact Pentaquark	Molecular state $D^{*} \Sigma_C$ (Karliner e Rosner)





EXTENSION OF THE GÜRSEY-RADICATI MASS FORMULA

We have just seen as only the $P_C^+(4380)$ resonance can be interpreted as a compact pentaquark, whyle the heviest one is a molecular state

We will concentrate only on the $P_C^+(4380)$ resonance

In order to determine the SU(3) flavour multiplet to whom belongs to the $P_C^+(4380)$ resonance, it has been necessary an extension of the GÜRSEY-RADICATI

THE GELL-MANN and OKUBO MASS FORMULA

The Gell-Mann and Okubo mass formula, takes into account the SU(3) breaking as due to the different masses of the quarks

Acording to that the mass M_{GMO} of a baryon belonging to a given SU(3) multiplet can be written as

$$M_{GMO} = M_0 + DY + E[I(I+1) - \frac{1}{2}Y^2]$$

M_0 is the avergae value of the SU(3) multiplet ;

Y is the baryon hypercharge
I is the total isospin

THE GÜRSEY-RADICATI MASS FORMULA

The Gürsey e Radicati mass formula is an extension of the Gell-Mann and Okubo's one, since it takes into account of the differentces in the masse values as due to as due to different spin of the baryons

$$M_{GR} = M_0 + AS(S+1) + DY + E[I(I+1) - \frac{1}{2}Y^2]$$

M_0 is the averge value of the masses of a given baryon SU(3) multiplet;

Y is the baryon hypercharge;
I is the total isospin;

S is the total spin of the baryon.

OUR EXTENCION OF THR GÜRSEY-RADICATI MASS FORMULA

La più semplice estensione della formula di massa, che tenga conto del contributo dei quarks c , e che discrimini i diversi multipletti di SU(3):

$$M_{GR}^{extended} = M_0 + AS(S+1) + DY + E[I(I+1) - \frac{1}{2}Y^2] + GC_2(SU_{fl}(3)) + Fn_c$$

M_0 is the average value of the masses of a given baryon SU(3) multiplet;

Y is the baryon hypercharge;
I is the total isospin;

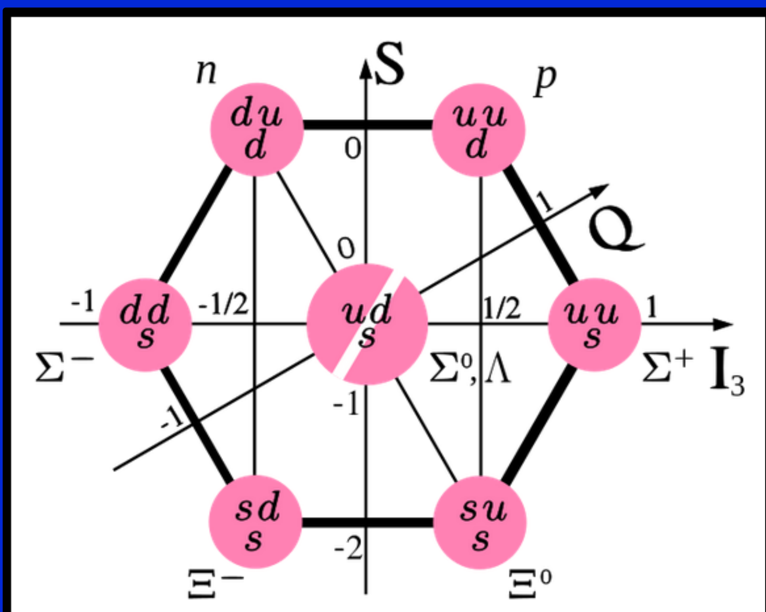
S is the total spin of the baryon.
C_2 (SU_{Fl}(3)) are the eigenvalues of the Casimir operator of SU_{Fl}(3);

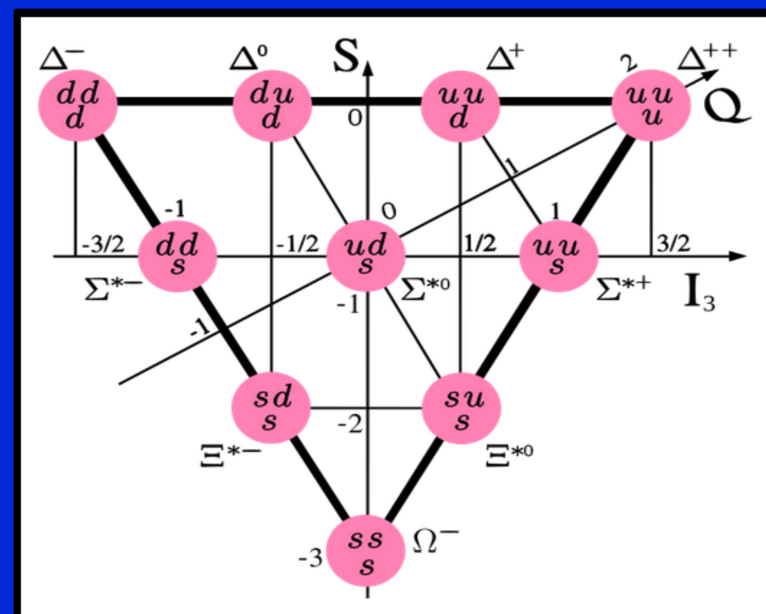
n_c counts the number of c or anti c quarks

OUR EXSTENSION of THE GÜRSEY-RADICATI MASS FORMULA

$$M_{GR}^{extended} = M_0 + AS(S+1) + DY + E[I(I+1) - \frac{1}{2}Y^2] + GC_2(SU_{fl}(3)) + Fn_c$$

The A, D, E, G and M_0 coeffiecients have been fixed using well known strange and non strange baryons





the F coefficient has been derived from charmed baryons

The decomposition procedure of the states

1) Decomposition of the $SU_{SF}(8)$ rapresentation, compatibile with the symmetry principle, into the spin and the flavour parts;

2) Since the lightest resonance has spin S=J=3/2, only the SU(4) represantation with spin 3/2 have been selected;

3) Only those representations have been further decomposed into $SU(3)XU_C(1)$, in such a way to select at the end only the SU(3) multiplet with charm quantum number C equal to zero;

Decomposition procedure of the states

4) In the most general case the ipercharge Y is defined as:

$$Y = B + S - \frac{C - B + T}{3}$$

since, for the ligthest pentaquark state is T=B=C=S=0, and B=1

Y=1

it is necessary to decompose further each SU(3) multiplet into $SU(2)XU_Y(1)$, and next step, select the multiplets with ipercharge Y=1

Decomposition procedure of the states

5) The mass of each multiplets has been calculated by means of an extension of the Gürsey e Radicati mass formula as already discussed

The multiplet with minimum energy is the octect of SU(3) , that is the [21] multiplet

$SU_{fl}(3)$ multiplet	$\supset SU_I(2) \otimes U_{Y=1}(1)$ submultiplets	mass (MeV)
$[51]_{35}$	$[5]_6$	5296
	$[3]_4$	5081
$[42]_{27}$	$[3]_4$	4729
	$[1]_2$	4600
$[3]_{10}$	$[3]_4$	4553
$[33]_{10}$	$[1]_2$	4424
$[21]_8$	$[1]_2$	4160

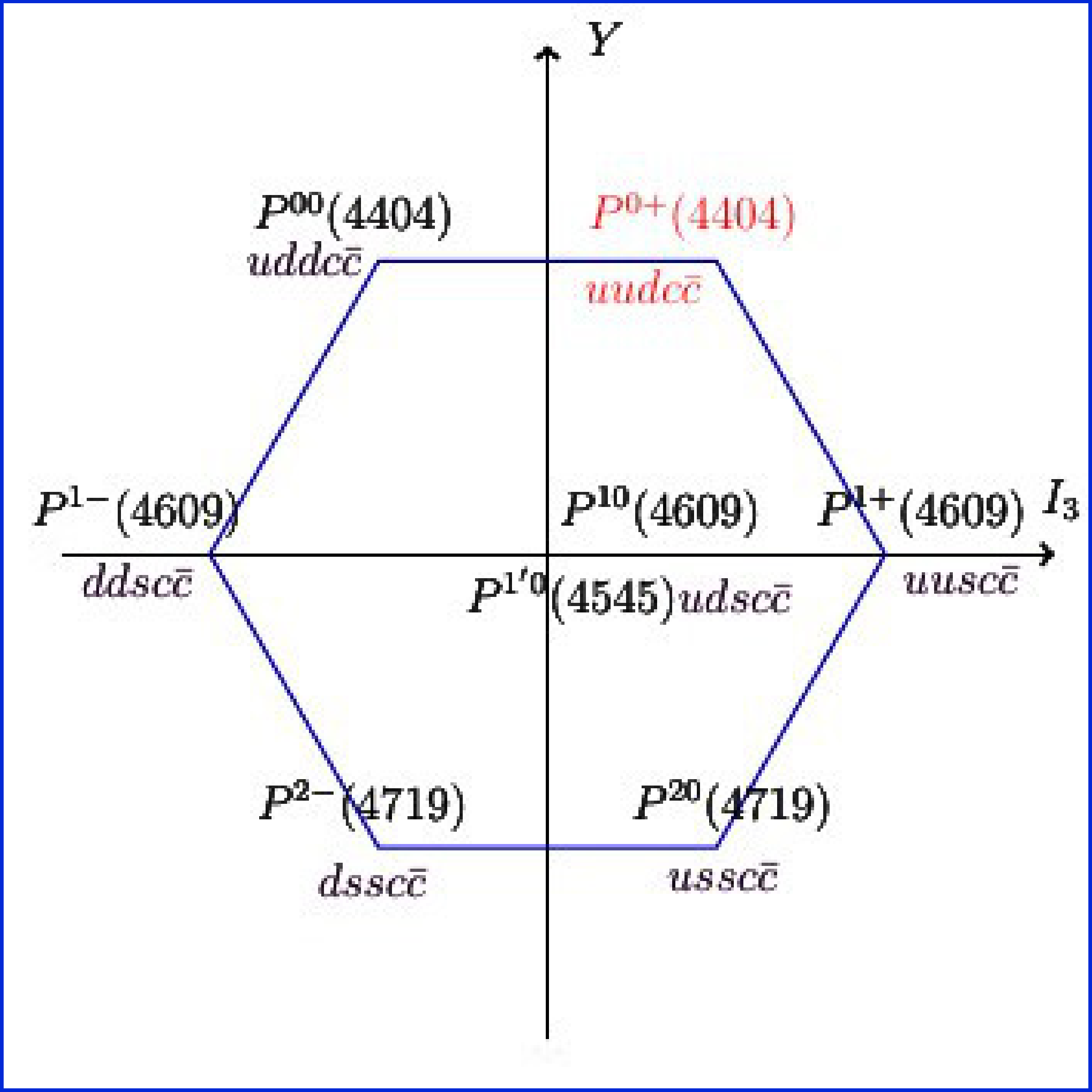
The lightest resonance, the $P_c^+(4380)$, acording to LHC_b
has a mass M = 4380 ± 8 ± 29 MeV
and a width W = 205 ± 18 ± 86 MeV

The predicted theoretical value of the mass is 4404 MeV in agreement with the exper. M = 4380 ± 8 ± 29 MeV

Notation:
$P^{IJ}(M)$ where
I is the number of s quarks;
J the electric charge;
M predicted mass

$SU_{fl}(3)$ multiplet	$SU_I(2)$ submultiplet	I	Y	mass (MeV)	isospin states
$[21]_8 \equiv$ 8	2	$\frac{1}{2}$	1	4160	$P^{00}(4160)$, $P^{0+}(4160)$
	S	0	0	4328	$P^{1'0}(4328)$
	3	1	0	4414	$P^{1+}(4414)$, $P^{10}(4414)$ $P^{1-}(4414)$
	2	$\frac{1}{2}$	-1	4540	$P^{20}(4540)$, $P^{2-}(4540)$

PENTAQUARK OCTECT STATES

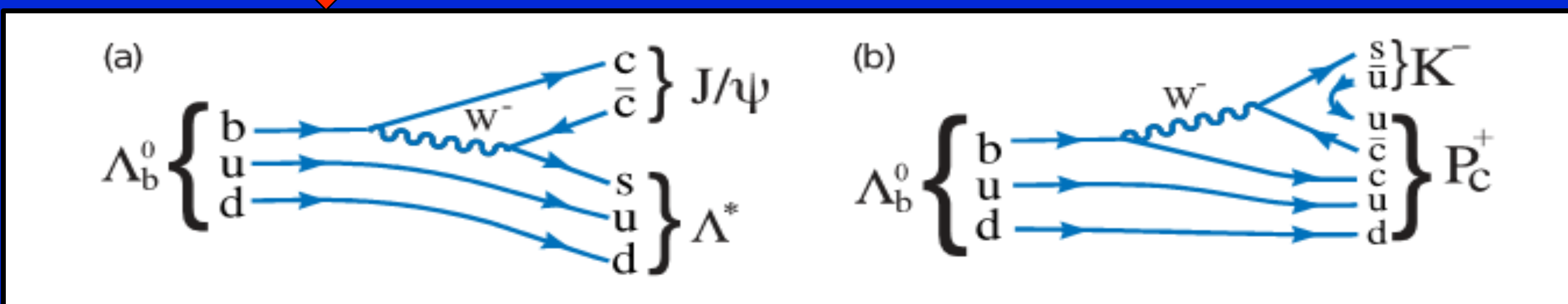


HOW TO OBSERVE OTHER PENTAQUARK STATES?

in order to give an answer to this question, we go back to study the decay channel in which the two pentaquark resonances have been observed

$P_c^+(4380)$ is part of an isospin doublet and it has been observed studing the Λ_b decay:

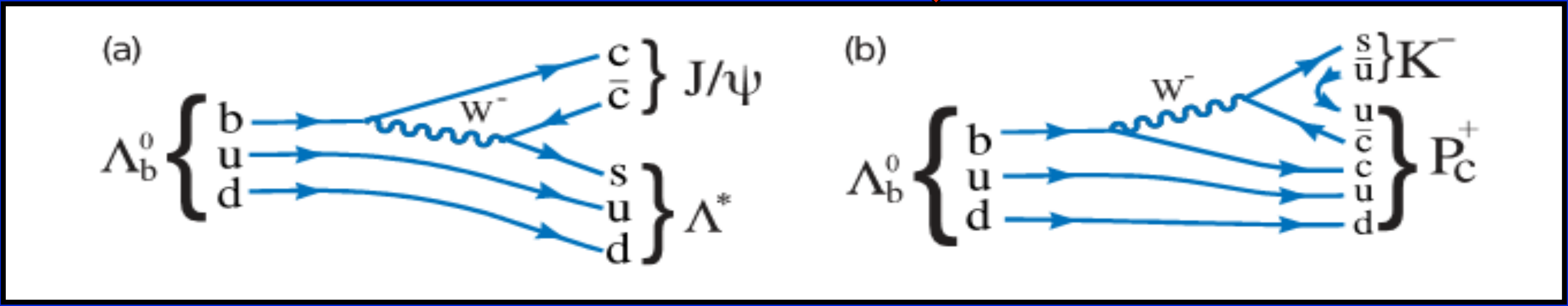
$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



HOW CAN WE OBSERVE PENTAQUARK STATES ?

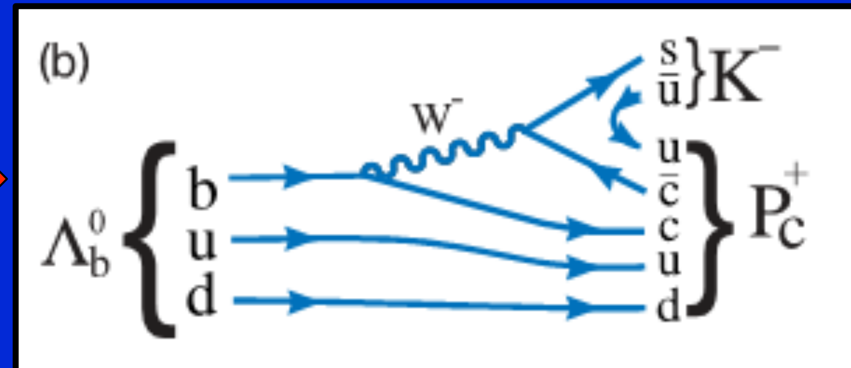
but,as seen, there is also the alternative decay channel that gives origin to the two pentaquark resonances:

$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



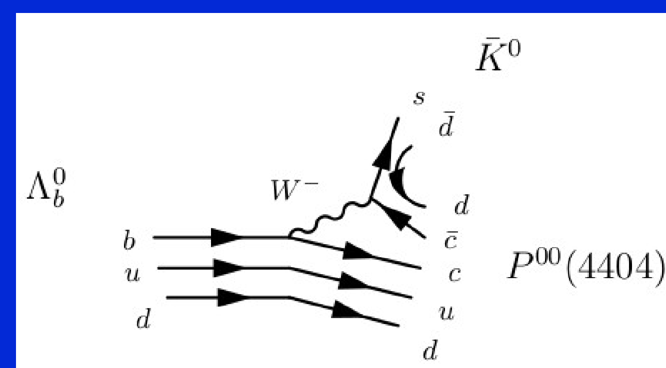
HOW TO OBSERVE OTHER PENTAQUARK STATES?

$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



In order to observe the isospin partner P^{00}(4160) of the charged P^{0+} we consider a pair creation of the type d anti d (instead of u anti u)

$$\Lambda_b^0 \longrightarrow P^{00} + \bar{K}^0,\ P^{00} \longrightarrow J/\Psi + n$$



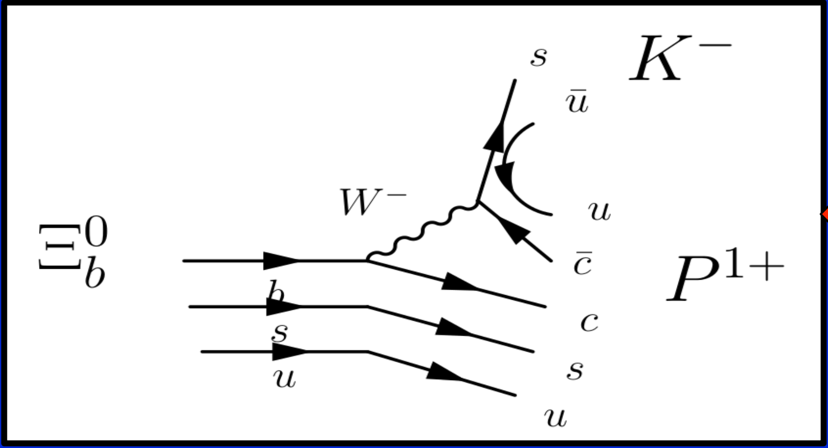
HOW TO OBSERVE OTHER PENTAQUARK STATES?

Regarding other pentaquark states with strangeness, we can consider bottomed baryon decays

$$\Xi_b^- \longrightarrow J/\psi + \Xi^-$$

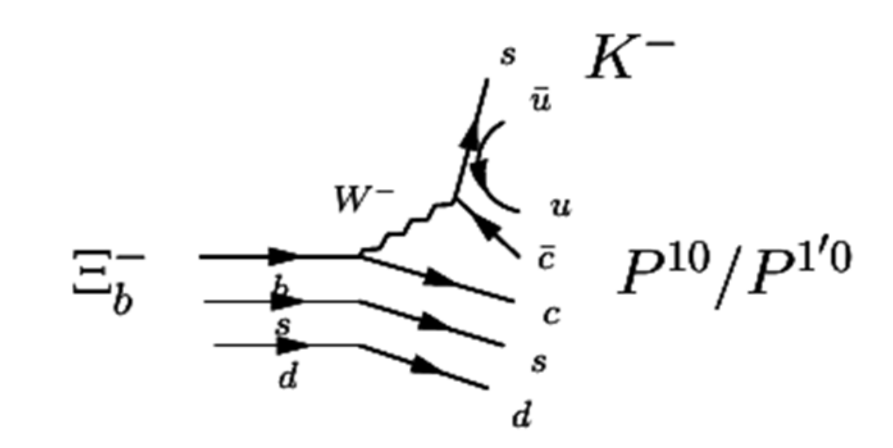
$$\Omega_b^- \longrightarrow J/\psi + \Omega^-$$

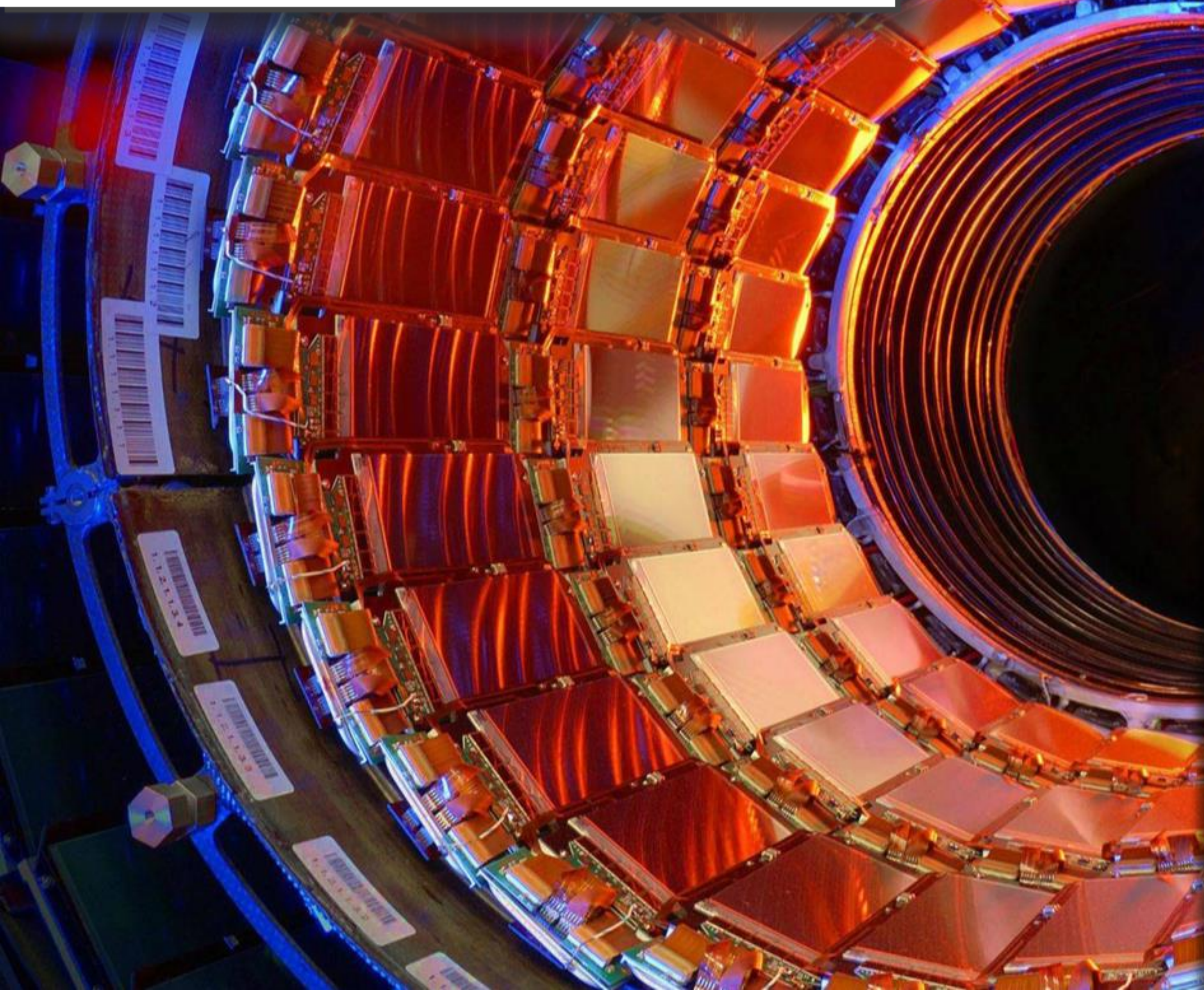
The charged $P^{1+}(4414)$ state is the most intresting from the experimental point of view, since all the final state particles are charged particles, so easier to be detected :

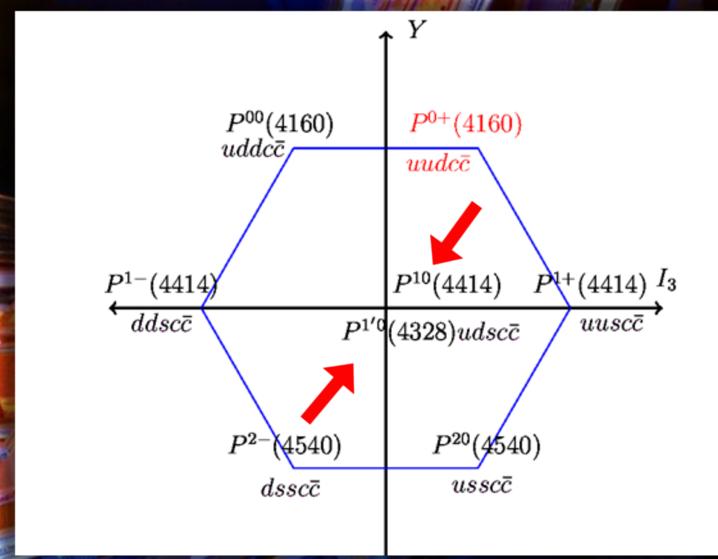


$$\Xi_b^0 \longrightarrow P^{1+} + K^-,\ P^{1+} \longrightarrow J/\Psi + \Sigma^+$$

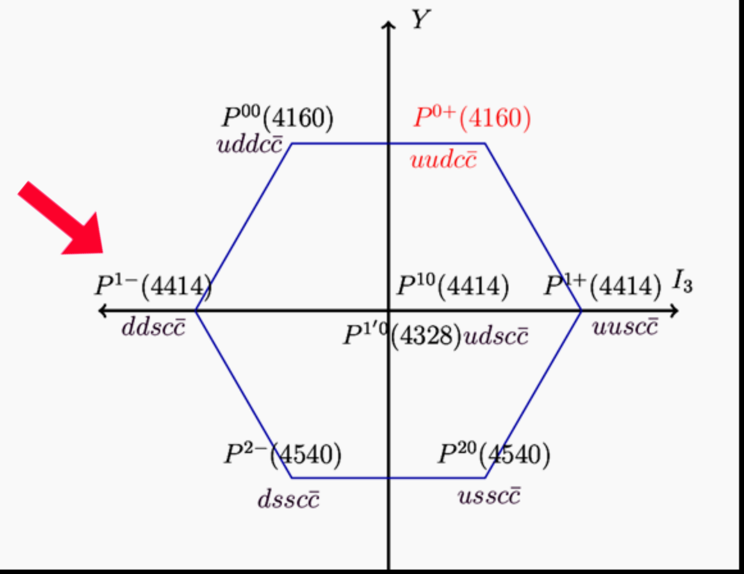
The states $P^{10}(4540)$ and $P^{1'0}(4328)$

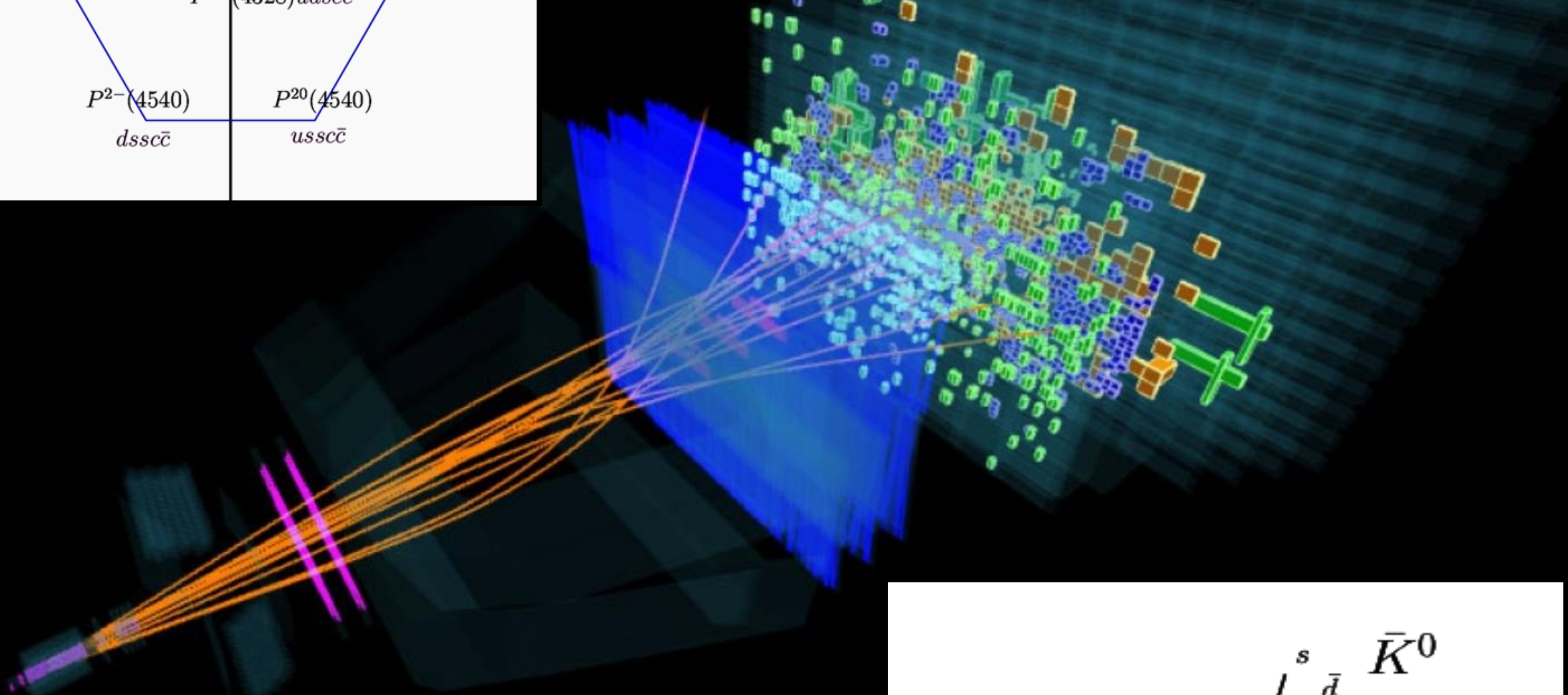


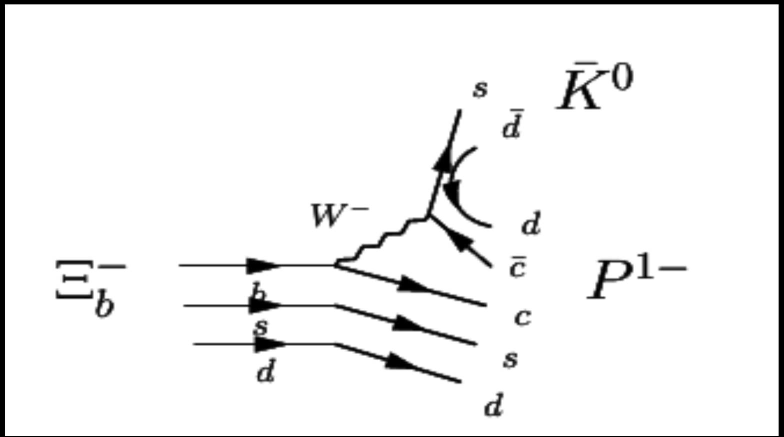




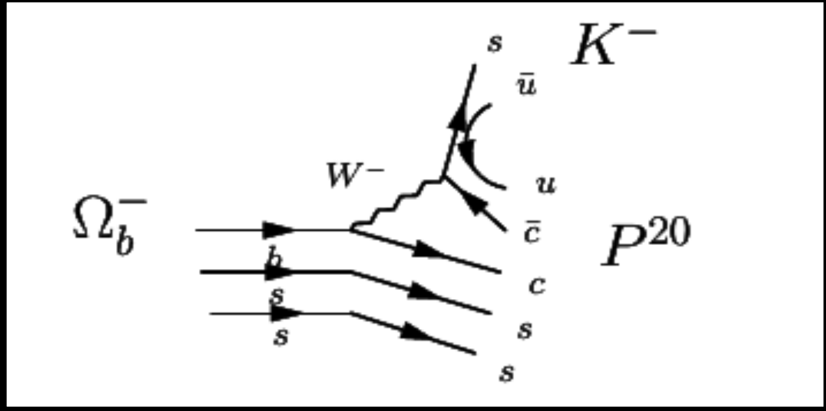
The $P^{1-}(4414)$ state

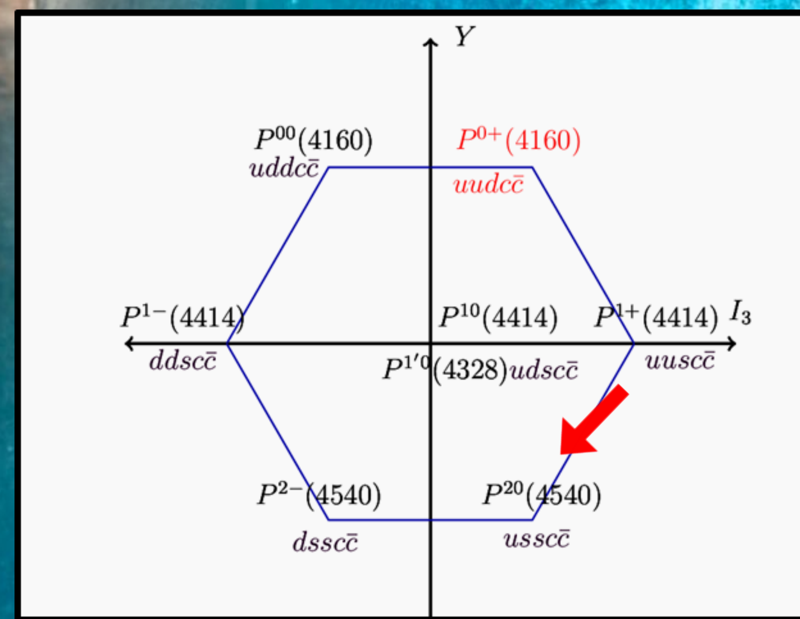


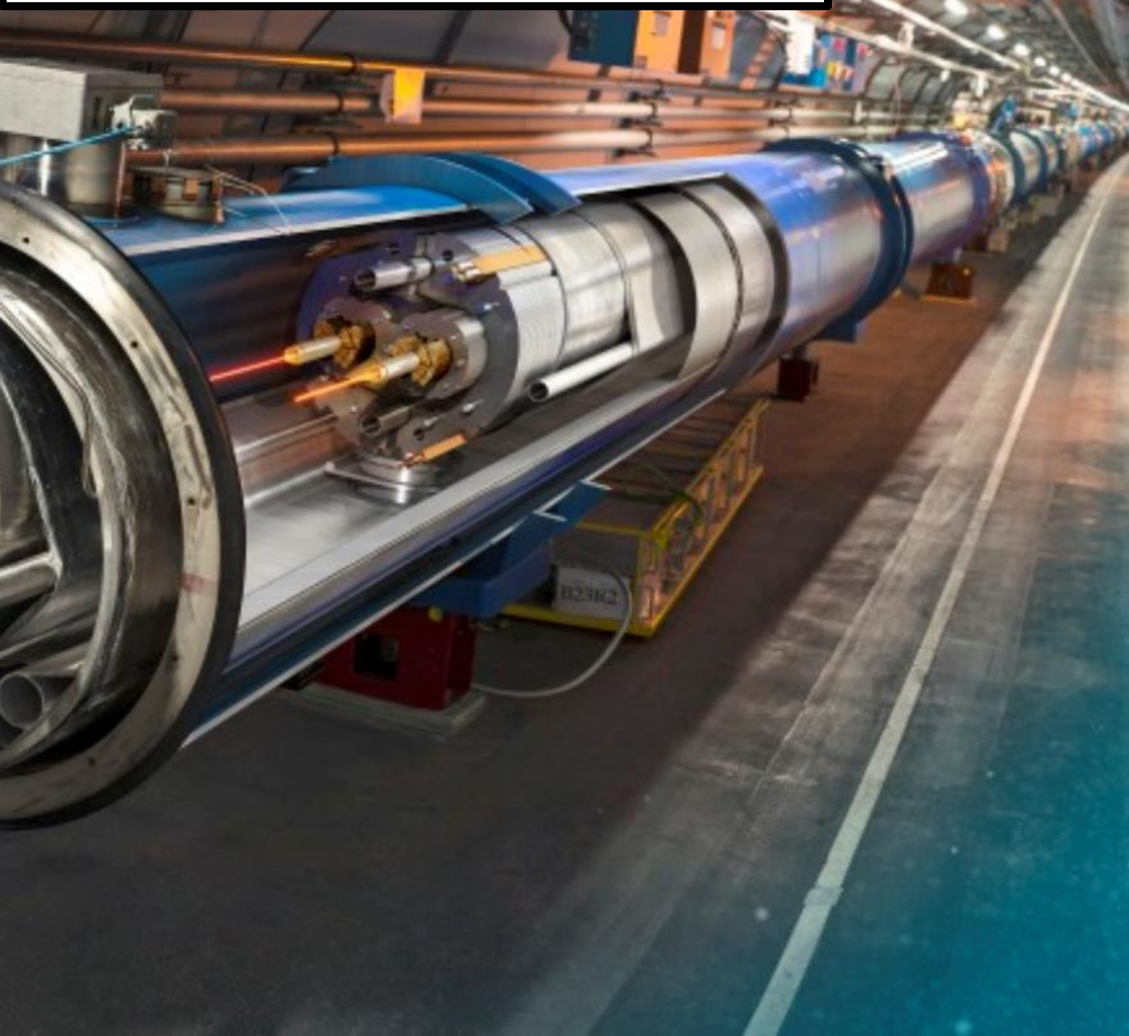




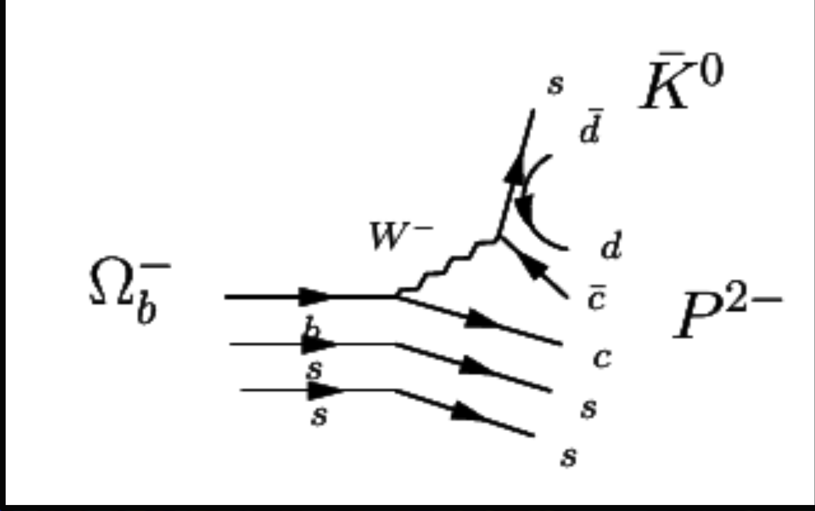
The $P^{20}(4540)$ state

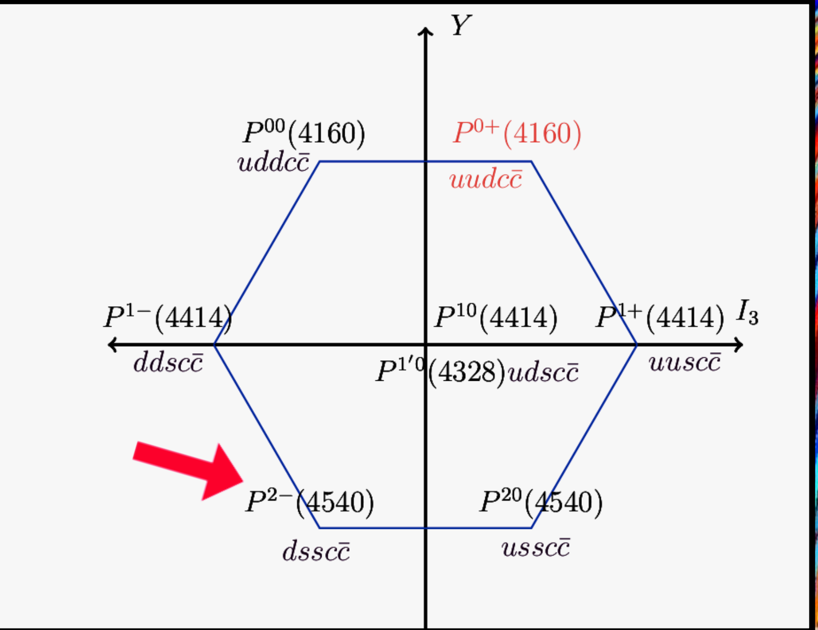






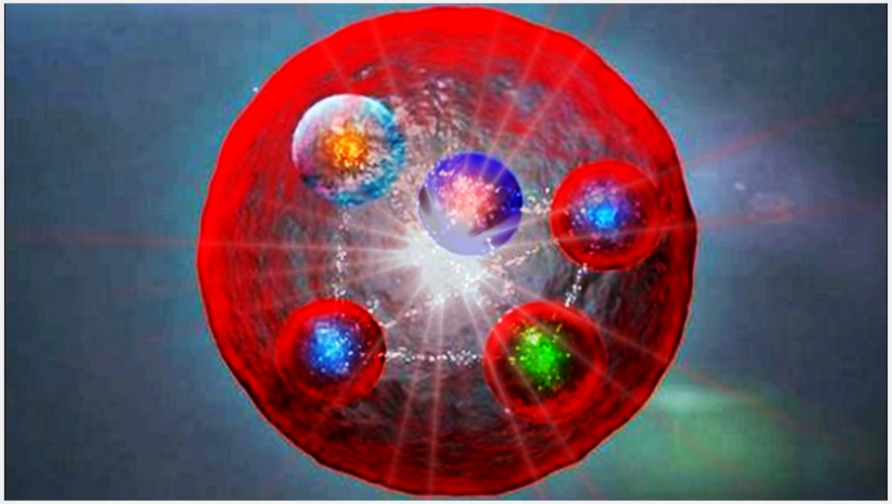
The $P^{2-}(4540)$ state

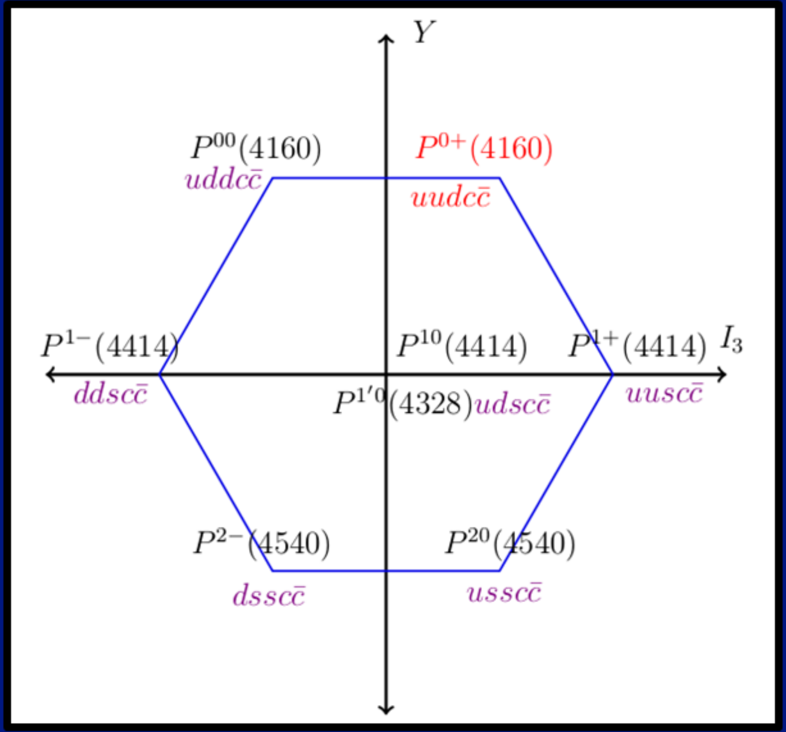




CONCLUSION

1) The $P_c^+(4380)$ state is well described by means of a compact pentaquark approach





2) Using group theory tecniques and with an extension of the GR mass formula, it has been demonstrated that it belongs to an SU(3) flavour octect

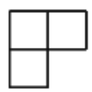
3) the compact pentaquark approach brings the existence also of other states, of which we have predicted the masses, and also suggested possible decay channels where the experimentalists can try to look for them


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

Thanks!

JEFFERSON Labroratory (JLAB) VG, USA

Sistema a tre quarks

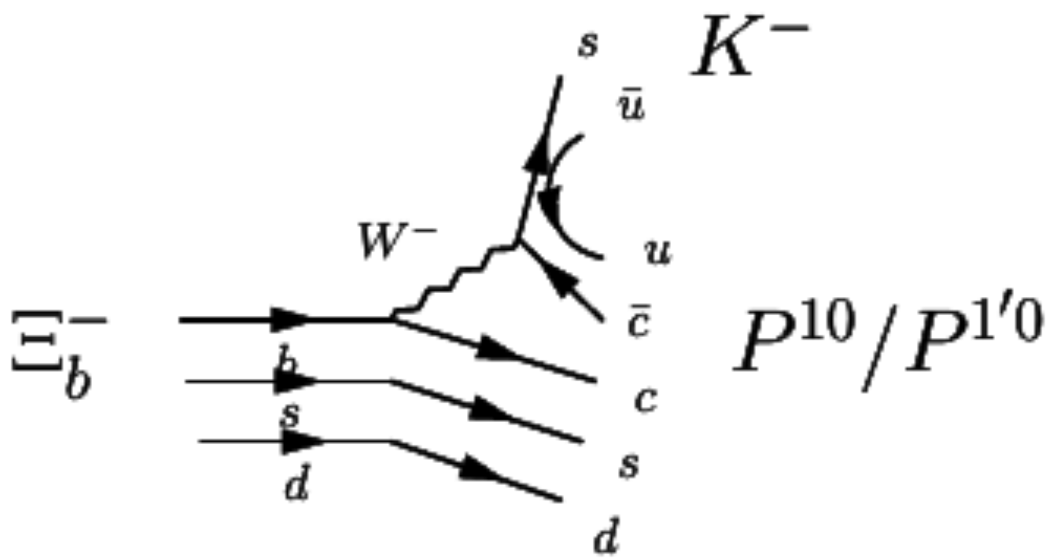
					Dimension		
D_3	$\sim$	S_3	Young tableau	Multiplicity	$SU_{sf}(8)$	$SU_{fl}(4)$	$SU_s(2)$
A_1	$\sim$	[3]		1	120	20	4
E	$\sim$	[21]		2	168	20	2
A_2	$\sim$	[111]		1	56	4	–

orbital symmetry	spin flavour symmetry	$q^4\bar{q}$ configurations
A_1	F_2	$[421^5]_{4752}$ $[21]_{168}$ $[3]_{120}$
F_2	A_1	$[51^6]_{2520}$ $[3]_{120}$
	F_2	$[421^5]_{4752}$ $[21]_{168}$ $[3]_{120}$
	E	$[331^5]_{2520}$ $[21]_{168}$
	F_1	$[3221^4]_{2800}$ $[21]_{168}$ $[111]_{56}$
E	F_2	$[421^5]_{4752}$ $[21]_{168}$ $[3]_{120}$
	F_1	$[3221^4]_{2800}$ $[21]_{168}$ $[111]_{56}$

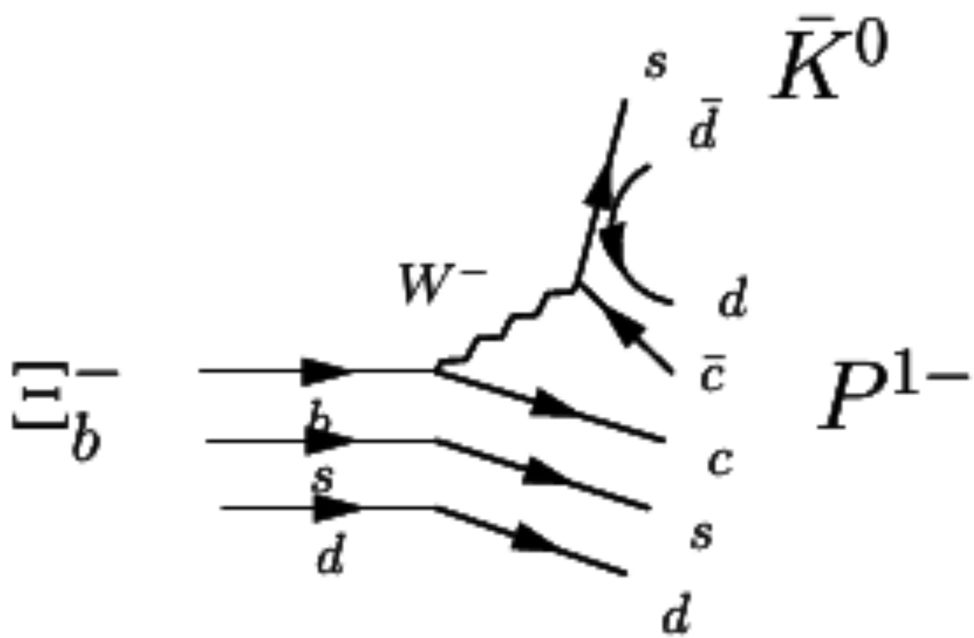
	A_1	F_2	E	F_1	A_2
A_1	A_1	F_2	E	F_1	A_2
F_2	F_2	$A_1 + F_2 + E + F_1$	$F_1 + F_2$	$F_2 + E + F_1 + A_2$	F_1
E	E	$F_1 + F_2$	$A_1 + E + A_2$	$F_1 + F_2$	E
F_1	F_1	$F_2 + E + F_1 + A_2$	$F_1 + F_2$	$A_1 + F_2 + E + F_1$	F_2
A_2	A_2	F_1	E	F_2	A_1

Symmetry	$SU_{sf}(8)$	$\supset$	$SU_{fl}(4)$	$\otimes$	$SU_s(2)$	multiplicity
F_2	$[421^5]_{4752}$		$[421]_{140}$	$\otimes$	$[1]_2$	2
			$[421]_{140}$	$\otimes$	$[3]_4$	2
			$[421]_{140}$	$\otimes$	$[5]_6$	1
			$[511]_{120}$	$\otimes$	$[1]_2$	1
			$[511]_{120}$	$\otimes$	$[3]_4$	1
			$[331]_{60}$	$\otimes$	$[1]_2$	1
			$[331]_{60}$	$\otimes$	$[3]_4$	1
			$[322]_{36}$	$\otimes$	$[1]_2$	2
			$[322]_{36}$	$\otimes$	$[3]_4$	1
			$[3]_{20}$	$\otimes$	$[1]_2$	2
			$[3]_{20}$	$\otimes$	$[3]_4$	2
			$[3]_{20}$	$\otimes$	$[5]_6$	1
			$[21]_{20}$	$\otimes$	$[1]_2$	3
			$[21]_{20}$	$\otimes$	$[3]_4$	3
			$[21]_{20}$	$\otimes$	$[5]_6$	1
			$[111]_4$	$\otimes$	$[1]_2$	1
			$[111]_4$	$\otimes$	$[3]_4$	1

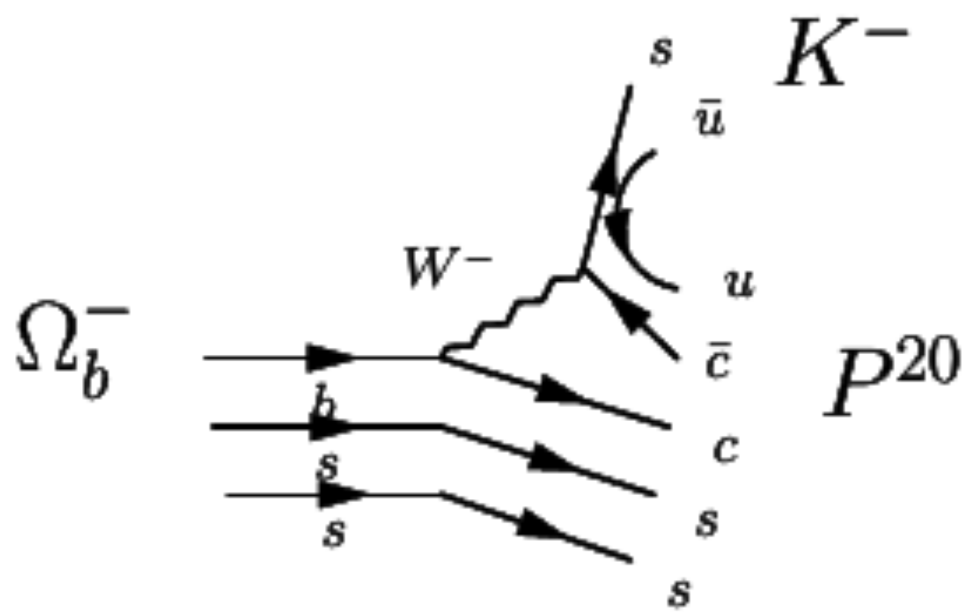
$$\Xi_b^- \longrightarrow P^{10}/P^{1'0} + K^-,\ P^{10}/P^{1'0} \longrightarrow J/\Psi + \Sigma^0/\Lambda$$



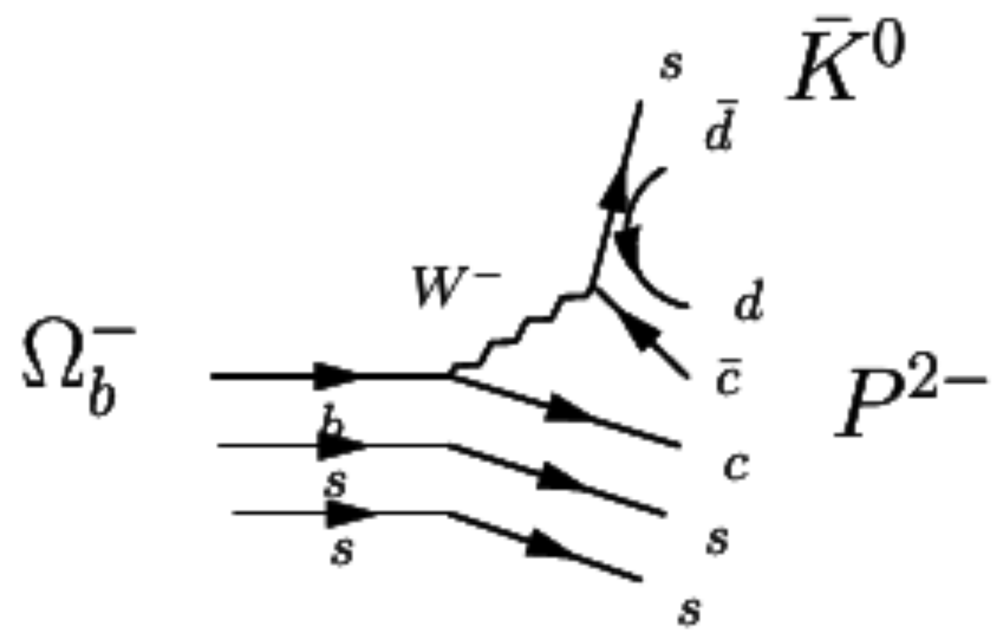
$$\Xi_b^- \longrightarrow P^{1-} + \bar{K}^0,\ P^{1-} \longrightarrow J/\Psi + \Sigma^-$$



$$\Omega_b^- \longrightarrow P^{20} + K^-,\ P^{20} \longrightarrow J/\Psi + \Xi^0$$

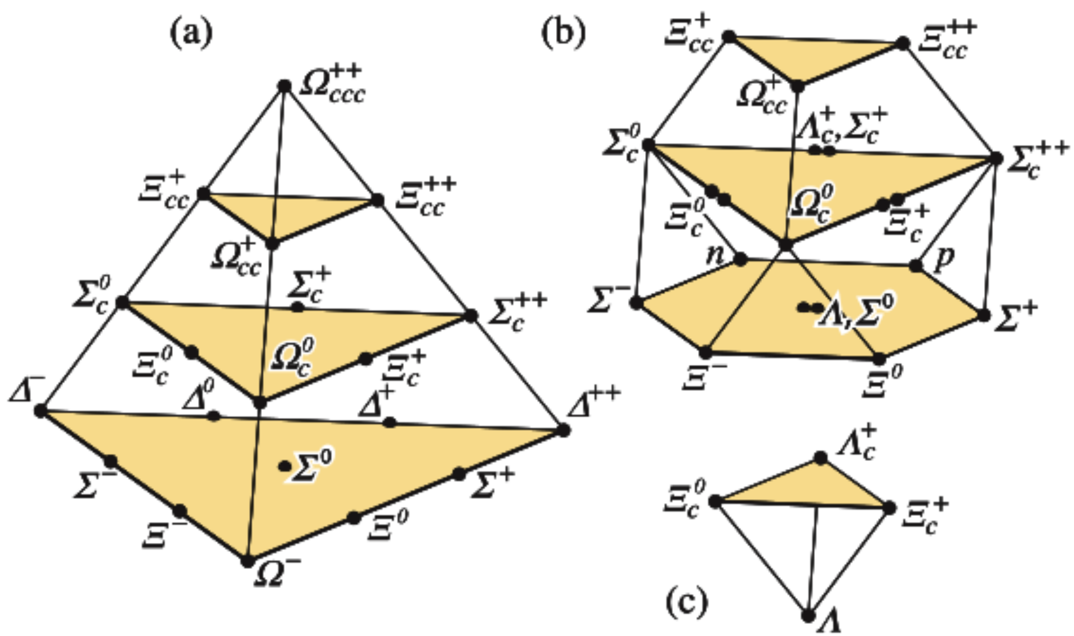


$$\Omega_b^- \longrightarrow P^{2-} + \bar{K}^0,\ P^{2-} \longrightarrow J/\Psi + \Xi^-$$



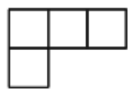
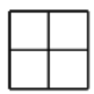
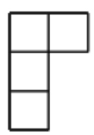
Dal Particle Data Group:

The flavor symmetries shown in Fig. 2 are of course badly broken, but the figure is the simplest way to see what charmed baryons should exist. For example, from Fig. 2(b), we expect to find, in the same $J^P = 1/2^+$ $20'$-plet as the nucleon, a Λ_c, a Σ_c, *two* Ξ_c's, and an Ω_c. Note that this Ω_c has $J^P = 1/2^+$ and is not in the same SU(4) multiplet as the famous $J^P = 3/2^+$ Ω^-.



Symmetry of the q^4 subsystem	$SU_{sf}(8)$ pentaquark states
$A_1 + F_2$	$[3]_{120}$
$F_1 + F_2 + E$	$[21]_{168}$
$F_1 + A_2$	$[111]_{56}$
A_1	$[51^6]_{2520}$
F_2	$[421^5]_{4752}$
E	$[3311111]_{2520}$
F_1	$[3221^4]_{2800}$
A_2	$[2^4111]_{504}$

Four quarks subsystem

					Dimension		
$\mathcal{T}_d$	$\sim$	S_4	Young tableau	Multiplicity	$SU_{sf}(8)$	$SU_{fl}(4)$	$SU_s(2)$
A_1	$\sim$	[4]		1	330	35	5
F_2	$\sim$	[31]		3	630	45	3
E	$\sim$	[22]		2	336	20	1
F_1	$\sim$	[211]		3	378	3	–
A_2	$\sim$	[1111]		1	70	1	–